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DUAL MECHANISMS FOR THE FORMATION OF FLUVIAL SILCRETES IN THE DISTAL REACHES OF THE OKAVANGO DELTA FAN, BOTSWANA

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ABSTRACT

Silcretes exposed within river-marginal or valley settings have been described in a number of studies, but few models have been suggested for the development of these 'fluvial' silcretes. An exception is that proposed by McCarthy and Ellery (*Journal of Sedimentary Research*, 1995, Vol. A65, pp. 77–90) to describe mechanisms of early stage near-surface silica diagenesis in the Okavango Delta, Botswana. This paper describes the characteristics and possible origins of massive surface and sub-surface silcretes at Samedupe and Boro Junction, beyond the distal margin of the Okavango Delta and further downstream than the sites described by McCarthy and Ellery. Morphological and petrological evidence from surface exposures and three sedimentary cores suggests that other modes of formation may also be applicable. A dual model of formation is proposed: surface silcretes are suggested to have developed by silica accumulation in seasonal pools remaining after the annual Okavango flood, whilst sub-surface horizons appear to have formed under conditions of varying pH associated with fluctuating groundwater levels beneath the channel floor. This model is reviewed in the context of the fluvial silcrete debate. © 1998 by John Wiley & Sons, Ltd.

KEY WORDS: silcrete; duricrusts; Okavango Delta; Kalahari; Botswana

INTRODUCTION

Siliceous duricrusts or silcretes have been identified on every continent except Antarctica, and are particularly widespread in Australia and southern Africa (Summerfield, 1983a; Watson and Nash, 1997). There is much debate in the geomorphological and geological literature concerning their origin and mode of development, with silica precipitation suggested to have occurred in a variety of geomorphological settings ranging from highly alkaline evaporitic basins (e.g. Ambrose and Flint, 1981; Renaut *et al*., 1986) to valley alluvium (e.g. Lindqvist, 1990; Ollier, 1991) and soil profiles (e.g. Auzel and Cailleux, 1949; Hutton *et al*., 1978; Thiry and Milnes, 1991). Many authors argue a hydrological control upon silcrete development (e.g. Stephens, 1971; Smale, 1973; Senior, 1978; Milnes and Thiry, 1992), particularly in locations where silcretes are found in conjunction with extant or fossil drainage features (Nash *et al*., 1994a, b; Nash, 1997).

Silcrete formation in a fluvial environment has been occasionally referenced in the literature, with silcretes currently exposed in riverine or valley settings assumed to have developed from the precipitation of river-transported solutes. However, in general, the provenance and mode of origin of silcretes formed in fluvial settings remain unclear (see Nash *et al*. (1994a) for a review). The only study to directly consider the processes of near-surface silica diagenesis in a fluvial setting is that of McCarthy and Ellery (1995), who have recently addressed the issue of silcrete formation in a single fluvial environment by examining silica accumulation in the distal reaches of the Okavango Delta, Botswana (as described below).

In this paper we examine two sites at Samedupe and Boro Junction at the distal margin of the Okavango Delta (Figure 1). At the former site a massive silcrete sheet occupies the entire width of a drainage channel and is associated with substantial sub-surface silica accumulations, whilst at Boro Junction similar sub-surface

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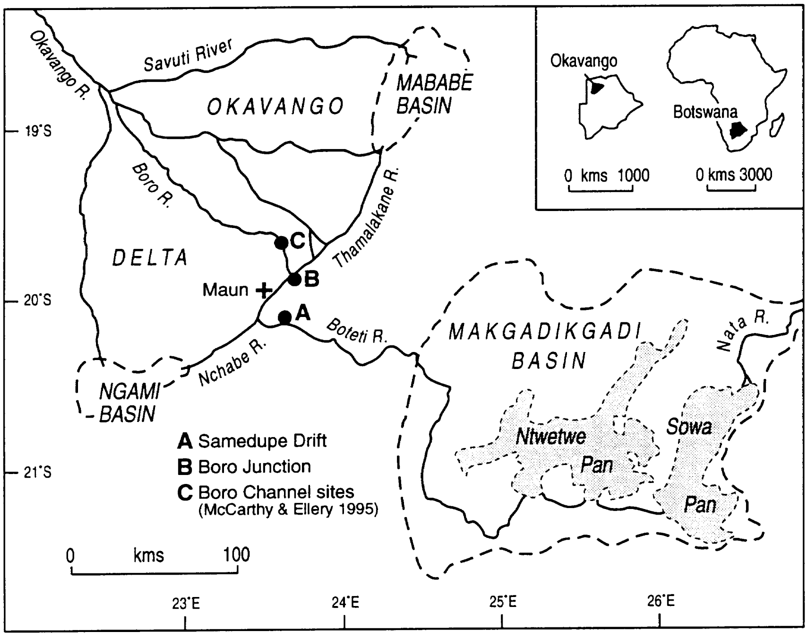

Figure 1. Map of the Okavango–Makgadikgadi system of northern Botswana, showing sites mentioned in the text

silcretes are identified from sedimentary cores. The morphology and micromorphology of the silcretes at these sites are considered, and mechanisms for their origin and development are suggested. The proposed model of formation agrees with many of the findings of McCarthy and Ellery (1995) for the development of silcretes presently exposed at the land surface. However, it is apparent from the silcretes at Samedupe and Boro Junction that the sedimentary environment described in the Okavango Delta by McCarthy and Ellery gives way, in the Delta outflows, to one in which the patterns of silicification may differ. As such, the silcretes described in this study provide evidence for the operation of two distinct mechanisms in the development of silcretes in a fluvial setting.

OCCURRENCES OF FLUVIAL SILCRETES

A number of studies have identified silcretes within or adjacent to drainage lines that have an assumed fluvial origin; however, very few studies have attempted to outline precise mechanisms for the precipitation of silica in such environments. Fluvial hypotheses of silcrete formation include those proposed by Stephens (1964, 1971), who postulated that the extensive silcrete sheet of central Australia formed by precipitation of silica dissolved in regional drainage waters, a hypothesis rejected by Brückner (1966) following a consideration of the lateral extent and uniformity of the silcrete horizon. More recently Summerfield (1982, 1983a,b) attributed silcretes formed in river channels in the Boteti and Nata Rivers (Figure 1) of the Middle Kalahari to a *per descensum* model (Goudie, 1973), where silica-rich waters have permeated down from the surface and subsequently led to the silicification of sub-surface host sediments. However, he also suggested that silcretes in this type of fluvial setting may have formed by evaporative concentration from an earlier pan or lacustrine environment, possibly in a proto-drainage line, rather than from the river itself. Summerfield (1983b) noted that both fluvial/sheetflood and lacustrine/pan models would necessitate lateral transfer of mobile silica. Mann and Horwitz (1979) have discussed the formation of calcretes in valley floors by both vadose and phreatic processes, with Arakel (1986) describing the silicification of pre-existing calcretes in a valley environment. Sequential downcutting through valley silcretes has been proposed as a mechanism for the formation of silcrete lenses in the Oligocene Fontainebleau Sand of the Paris Basin (Thiry *et al.*, 1988), a process further explored by Nash *et al.* (1994a) in the Kalahari.

The only formational model for silica precipitation from river water is that of McCarthy and Ellery (1995) who describe early stages of silica diagenesis within sediments along the margins of the Boro Channel in the Okavango Delta, Botswana. They propose a model of accumulation of clastic material and phytolithic silica from the annual Okavango floodwaters, alongside precipitation of fine-grained amorphous silica from groundwater induced by transpiration from aquatic grasses. The fine silica layers produced by the combination of these mechanisms, although largely unlithified proto-silcretes representing the early stages of near-surface silica diagenesis, are considered to be analogues for ganisters in ancient sedimentary rocks. Such analogies have been pursued in the past (e.g. McDonnell, 1974; Wopfner, 1978), but without vigour. The range of hypotheses for the development of silcretes exposed in fluvial settings so far proposed suggests that, for the debate to advance, further consideration should be given to both the environments and mechanisms of silcrete formation.

THE OKAVANGO DELTA AND ITS SILCRETE EXPOSURES

The characteristics of the Okavango Delta have been described by a number of authors (e.g. Thomas and Shaw, 1991; McCarthy and Ellery, 1995). Essentially, it is an alluvial fan covering approximately 20 000 km^2, formed where the Okavango River enters a half graben of the Kalahari Rift in northern Botswana (Shaw and Thomas, 1993). The Delta receives some $11\times10^9\,m^3$ inflow and $5\times10^9\,m^3$ rainfall per year, with the majority of the inflow arising from Okavango tributary streams in the Angolan Highlands. Whilst rainfall over the Okavango Delta occurs in southern hemisphere summer months, the inflow peak from the Angolan Highlands occurs around February in the upper Delta, reaching the distal end four months later. Some 96 per cent of the water in the Delta is lost through evapotranspiration, estimated at $1860\,mm\,a^{-1}$ (Wilson and Dincer, 1977). The remaining 4 per cent is lost as groundwater flow and as surface flow at the Delta extremities, of which the most important outflow is the Thamalakane River. The Thamalakane bifurcates into the Boteti and Nchabe Rivers, draining to the Makgadikgadi and Ngami Basins, respectively. There has been considerable variation in flow through the Delta on both historical (Shaw, 1984) and Quaternary (Shaw, 1988) time scales, with the present flow regime amongst the lowest on record.

Although solute levels in the river water intake are low (<30 ppm), budgetary studies (McCarthy and Metcalfe, 1990) suggest that precipitation of salts leads to the accumulation of some 450 000 tons a^{-1}, exceeding the clastic load by up to a factor of two. Two salt precipitation gradients are apparent, one represented by the concentration of solutes downstream (Dincer *et al.*, 1978; Summerfield, 1982), and the other by lateral absorption of salts through fringing swamps into islands (McCarthy *et al.*, 1986). These precipitation gradients lead to the separation of highly soluble salts from calcium carbonate and silica, which concentrate in the lower Delta, and beyond that into the Boteti River and Makgadikgadi Basin, where separate calcrete and silcrete provinces have been identified (Shaw *et al.*, 1991). Solute concentration by progressive evapotranspiration downstream has been confirmed by a number of studies (e.g. Hutton and Dincer, 1976; Summerfield, 1982; Sawula and Martins, 1991), though the pattern is complicated by locational and seasonal variation.

There are no known surface exposures of silcrete within the Okavango Delta itself (SMEC, 1989); the first lies downstream at the Thamalakane–Boteti/Nchabe bifurcation. They occur thereafter in both the Boteti and Nchabe Rivers as sills or bars up to 400 m long, which act as ponding controls on surface flow. Similar features have been described from the Nata River where it enters the Makgadikgadi Basin (Macgregor, 1932; Smale, 1973; Summerfield, 1982). Both the Boteti and Nchabe are misfit channels (Shaw *et al.*, 1988), whose original larger dimensions relate to the function of the Quaternary Okavango–Makgadikgadi palaeolake system (Thomas and Shaw, 1991).

DESCRIPTION OF THE SAMEDUPE SURFACE SILCRETES

The silcrete exposure at Samedupe Drift (Figure 2a) lies 18 km downstream of the Thamalakane bifurcation and is the largest on the Boteti River, taking up the 180 m width of the channel bed and extending approximately 400 m downstream. A narrow floodplain bounds the channel, beyond which terrace deposits rise to approximately 8 m above the channel bed and extend to 500 m on either side. The exposure has long been

(a)
(b)
(c)

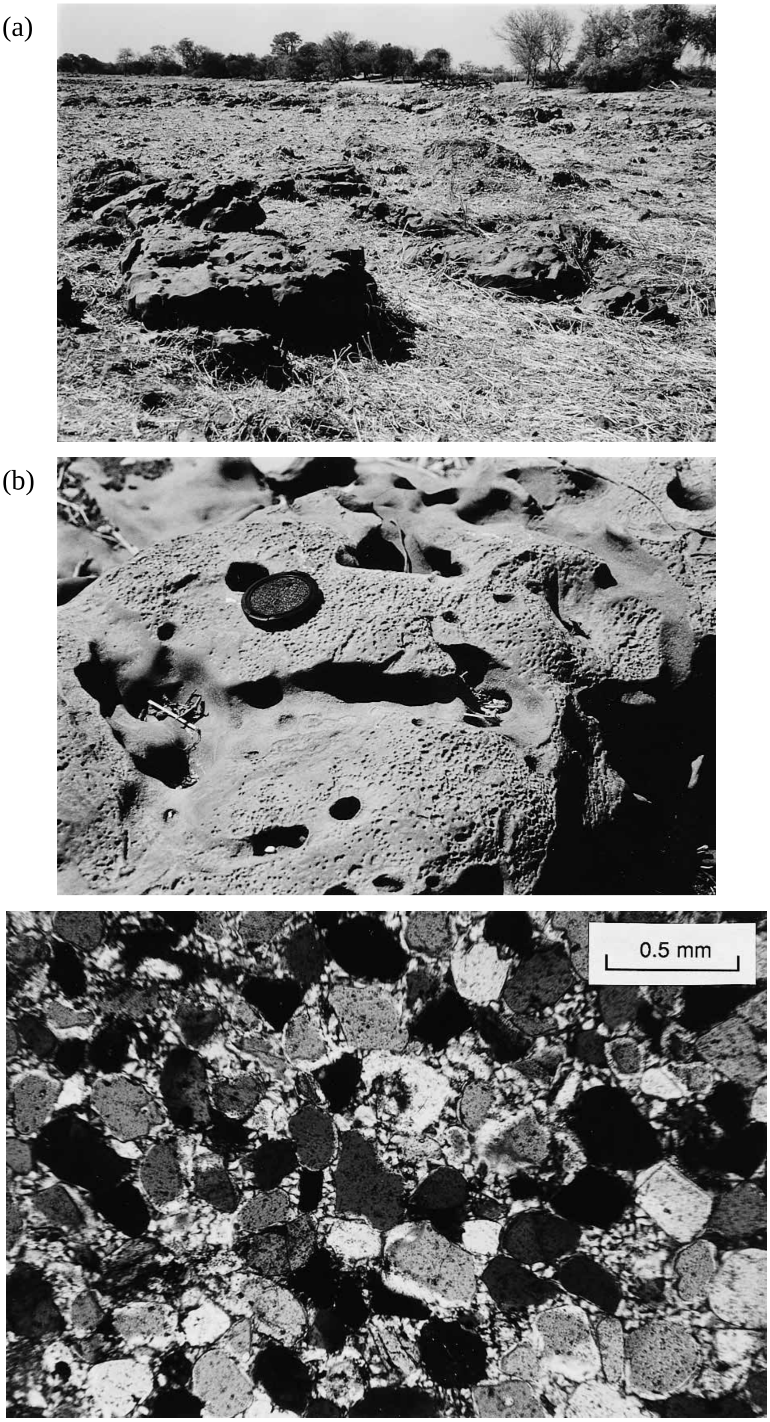

Figure 2. (a) The silcrete exposure at Samedupe Drift, looking upstream. (b) A block of Samedupe silcrete showing macro-features including tubes and solutional pitting. (c) Petrographic thin section of Samedupe silcrete showing well-cemented grain-supported fabric of rounded quartz grains. The cement consists of disordered length-fast chalcedony and cryptocrystalline silica with little void space (crossed-polarized light)

recognized as an important archaeological site, with the silcrete being used as material for stone tools from the Early Stone Age onwards (Wayland, 1950; Cooke, 1979).

Silcrete occurs as a series of upstanding blocks as much as 3 m in length and 1 m in height, giving the appearance of being the remains of a continuous silcrete sheet buried in the river bed (Figure 2b). The blocks exhibit a highly variable surface morphology dominated by hollows, interconnecting tubular structures and a prominent weathering rind. The rind appears to be case-hardened, and differential erosion occurs where it has been removed. Tubes range in diameter from 18 mm to 45 mm and have no overall dominant direction. In hand specimen the silcretes vary from pale brown to buff or grey in colour with minor patches of deep red staining. The material is extremely hard and well-indurated with a saccharoidal texture, almost vitreous lustre, and conchoidal fracture. The weathering rind is up to 12 mm thick and bounded by a 3 mm zone of iron oxide staining. In parts a decrease in cementation in the rind leads to a more friable structure and is suggestive of volumetric loss.

In thin section (Figure 2c) the silcrete consists of an extremely well cemented grain-supported fabric (cf. Summerfield, 1983b) containing moderate to well-rounded quartz grains up to 0·75 mm diameter. There are also minor floating fabric components, giving the silcrete the appearance of being formed by cementation of voids within a quartzose host material. In addition to the quartz component there are trace quantities of microcline feldspar and assorted heavy minerals. These are cemented within a disordered length-fast chalcedony and almost isotropic cryptocrystalline silica matrix with less than 0·5 per cent void space. The contact between the chalcedonic matrix and the skeletal grain material is sharp, with little evidence of grain overgrowths. The silica micromorphology suggests that the primary formational process has been simple cementation from silica-rich porewaters with no displacement of clastic grains.

THE SAMEDUPE AND BORO JUNCTION CORES

Two cores were extracted by rotary drilling as part of preliminary site investigations for a proposed dam at Samedupe (SMEC, 1987) (Figure 3). Core 4101 reached a depth of 16 m in the centre of the channel, whereas core 4102, of 20 m depth, was sited on the floodplain to the north of the channel with the borehole collar at an elevation approximately 2 m higher than core 4101. Both cores penetrated relatively unconsolidated sand in the first 4 m, grading down into a green-white calcareous sandy clay, interspersed with multiple massive silcrete horizons and discontinuous silcrete lenses. The characteristic brown colour of the surface silcrete is not found in sub-surface horizons, which are dominantly pale to medium green, a colour which has been reported from channel silcretes in Okwa Valley of the Kalahari (Nash *et al*., 1994b). The thicker horizons contained pisolithic structures up to 1 cm in diameter. Laminar silcretes throughout the cores graded both upwards and downwards into silicified sands. There is no direct correlation between the two cores, although it is possible that the green silcrete horizon at 4 to 5 m depth in core 4102 is equivalent to the brown silcrete at the surface of core 4101. If this is the case then there is a 2·5 m difference in height between the two horizons suggesting that the silcrete body slopes away from the channel axis. This relationship has been noted elsewhere in valley-marginal duricrusts in the Kalahari (Nash *et al*., 1994a).

X-ray diffraction analysis shows the green coloration to be caused by the presence of glauconite, suggesting an anaerobic environment at the time of precipitation. Calcareous nodules and thin laminar calcretes (comprising cemented nodules) were present at varying depths within clay and sandy-clay strata, but not within sand. Whereas the features of the silcretes and calcretes suggest that they formed by post-depositional modification of the fluvial sediments, hiatuses in deposition are represented by thin lenses of white, well-sorted sand, probably laid down as channel deposits.

Core 4103 was taken from Boro Junction, a site on the floodplain of the Thamalakane, close to the bifurcation of the Boro channel. The site was located some 600 m from the channel, close to the floodplain margin. Although 30 km upstream of the nearest surface silcrete exposure, the core exhibits the same subsurface characteristics as those from Samedupe. These include silcrete layers, calcrete horizons and lenses of unconsolidated sand, with one pisolithic silcrete horizon exceeding 1 m in thickness. The presence of multiple silcrete horizons within a core at this location suggests that sub-surface silcrete formation may be the norm in the lower Okavango Delta far upstream of visible surface exposures.

Examination of the pisolithic horizon at 4·8 m depth in core 4103 shows the pisoliths to be spheroidal to columnar when viewed in the vertical plane, with clear concentric development and a diameter varying

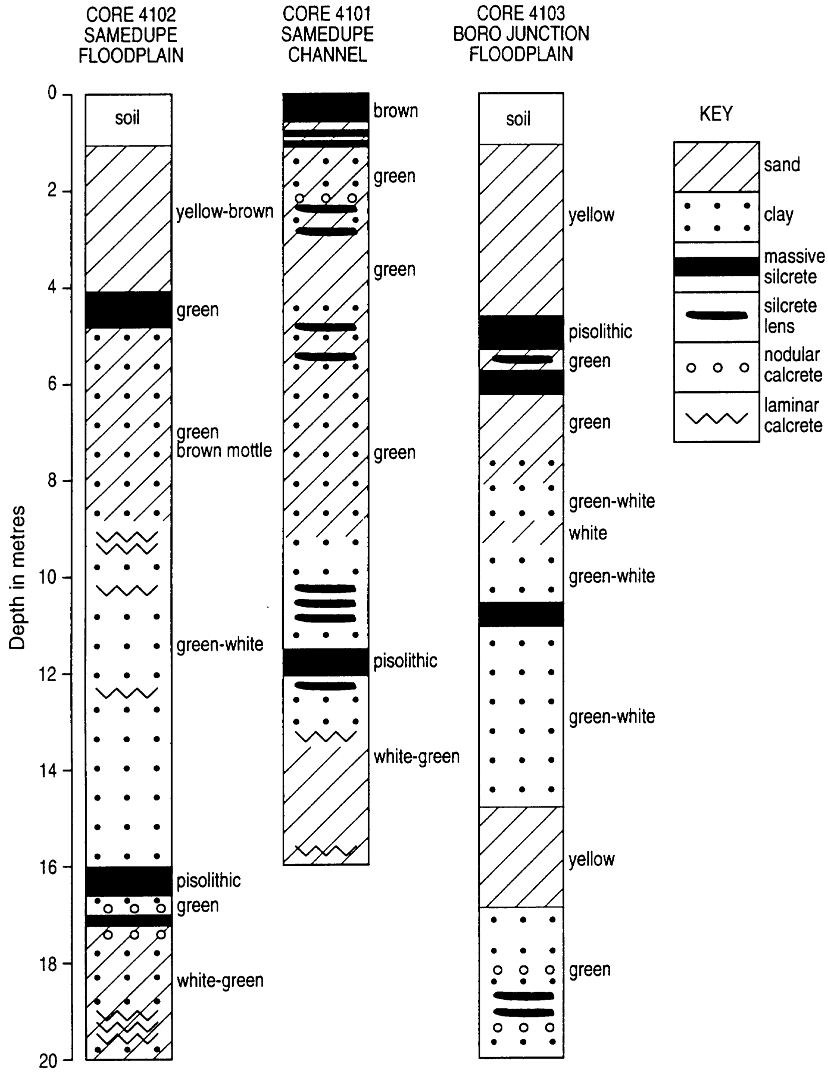

Figure 3. Core logs from Samedupe and Boro Junction

between 5 and 15 mm. The pisoliths are pale grey to green in colour, with a white outer crust surrounding individual and coalesced pisoliths. The inter-pisolith spaces generally contain red-brown silica. Many of the larger pisoliths, and those that have coalesced, display dissolution with voids on concentric layers. In general the material is extremely well-indurated with a vitreous lustre.

In thin section (Figures 4a and 4b) the concentric structure of the pisoliths clearly shows alternating phases of silica and calcium carbonate deposition, with phases of carbonate precipitation often associated with silica dissolution. Disordered length-fast chalcedony dominates the centre of pisoliths and is commonly surrounded by layers of isotropic cryptocrystalline silica. Carbonate zones are present as concentric rings of well-developed rhombohedral calcite crystals. There are no skeletal grains present within the pisoliths, suggesting that precipitation has taken place either within, or by the replacement of, clay-rich sediments. The micromorphological evidence suggests that formation of the pisolithic silcrete layers has taken place under conditions of alternating pH values, since the solubility of calcium carbonate and silica is inversely related to pH; precipitation of amorphous silica is known to occur below approximately pH 9 (Williams *et al.*, 1985; Williams and Crerar, 1985) whilst calcium carbonate rhombs would only begin to develop at pH values of >9

(a)

(b)

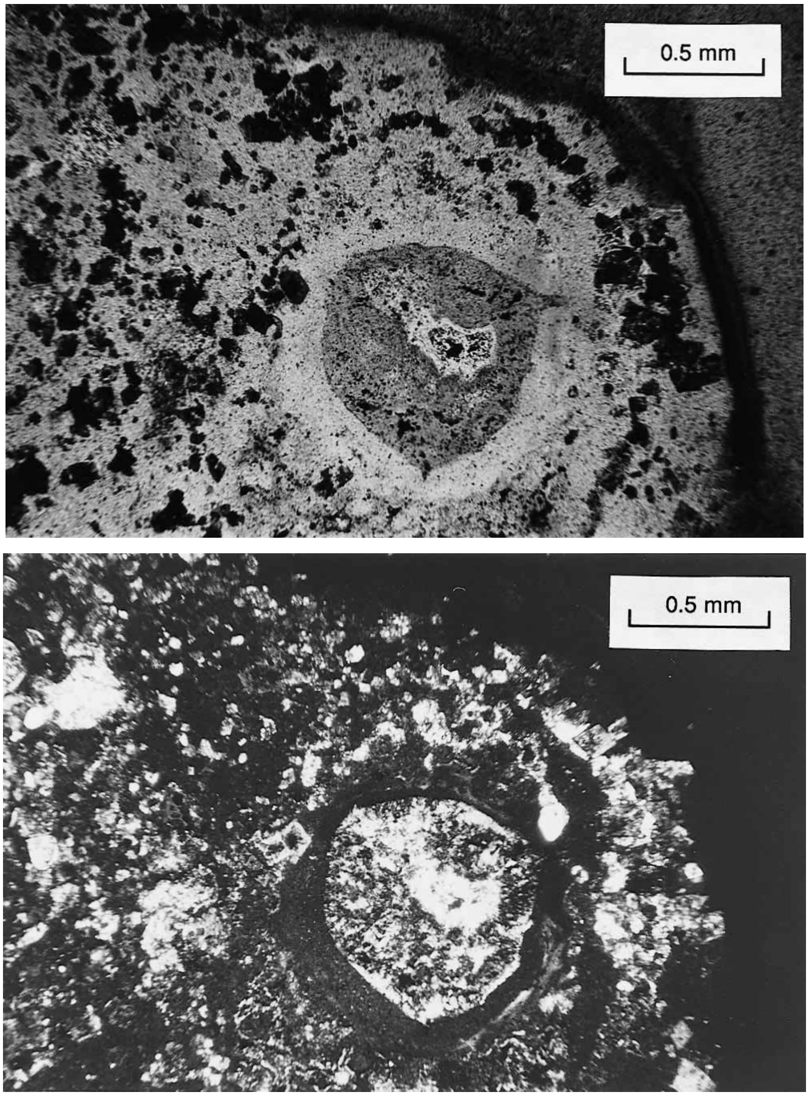

Figure 4. Petrographic thin sections of the pisolithic silcrete from the Boro Junction core at 4·8 m depth: (a) plain polarized light; (b) crossed-polarized light. The pisolith core comprises disordered chalcedony and cryptocrystalline silica surrounded by alternating layers of silica and rhombohedral calcite crystals

(Goudie, 1983). The pH conditions during phases of carbonate precipitation would be conducive to the dissolution of recently precipitated silica, with some dissolution of calcite layers likely to take place during the precipitation of silica.

ENVIRONMENTS OF SILCRETE FORMATION

In the absence of contemporary water chemistry data from the lower Okavango and Boteti River areas, it is not possile to specify the precise chemical environments of silcrete formation. However, the exposures at Samedupe and associated core evidence from Boro Junction and Samedupe suggest that different processes of silicification may operate in near-surface and sub-surface environments, respectively, as a result of the interaction of surface and groundwater. The massive surface silcrete sheet at Samedupe appears to represent cementation of sand by silica-rich porewaters and is consistent with the present hydrological system which replenishes both groundwater and surface water on an annual basis, the latter persisting as pools until the next

flood. These pools, which have supported dense stands of aquatic vegetation in the historical past (e.g. Livingstone, 1858), provide the ideal environment for the processes outlined by McCarthy and Ellery (1995); an annual input of clastic material and phytolithic silica, and an increasing pH and silica accumulation due to evaporation and transpiration, respectively. Silcrete accumulation in these pools would become self-perpetuating in that once a silcrete horizon forms it becomes an effective ponding agent. As Mann and Horwitz (1979) suggest for the development of phreatic calcretes, the presence of a localized silcrete layer within a channel would, once exposed at the surface, cause flow diversion and ultimately lead to the zone of crust formation extending laterally across the channel with time.

The formation of the sub-surface silcrete layers, particularly the pisolithic horizons, cannot, however, be explained by the same mechanism of formation as that proposed by McCarthy and Ellery (1995). As noted above, the petrology of the pisolithic material suggests accumulation of silica and carbonate in an environment which experiences fluctuating pH conditions. The most likely environment for such pH shifts is within the vadose zone beneath the channel floor, relatively close to the water table. In this environment, conditions would change from unsaturated to saturated with the passage of the annual flood, with associated shifts in pH from relatively high levels to lower levels. It is known that the annual flood through the Okavango Delta recharges the groundwater below the floors of its outflow channels. Borehole and piezometer records from the margins of the Thamalakane channel in the Maun area (SMEC, 1987) indicate that the groundwater level declines rapidly away from the channel, with corresponding increasing salinity and an increase in pH. Wells adjacent to the channel showed a rapid and direct response to the annual flood wave, whilst piezometers at the margin of the floodplain showed little response in level. A total dissolved solids concentration of the order of 3000 ppm in the Maun area suggests infrequent recharge. SMEC (1987) concluded that the Boro was a source of recharge for the near-surface aquifer, but that the steep gradient of the phreatic level implied low transmissivity in the floodplain sediments.

The location of the thick pisolithic silcrete bands in the cores depicted in Figure 3 appears to reflect the relative position of the vadose boundary beneath the channel floor, with increasing depth downstream from Boro Junction to Samedupe, and increasing depth laterally at Samedupe. This suggestion is supported by the presence of nodular calcrete horizons which are forming contemporaneously by precipitation from groundwater beneath islands within the Okavango Delta, with formation related to the height of the water table (McCarthy *et al*., 1986, 1991). It is probable that silica accumulation responds to rapid changes in pH due to fluctuating groundwater levels brought about by the passage of the annual floodwaters, together with an associated annual recharge of low salinity water through the channel floor sediments.

Two factors appear to explain why silcretes are not present in the Okavango Delta itself but are found in the distal channels. First, massive surface silcretes only occur in areas where the contemporary river flow has a high total dissolved solids level (Thomas and Shaw, 1991), suggesting that the occurrence of silcrete at the distal margins is partly controlled by the salt precipitation gradient identified throughout the Delta system (Summerfield, 1982; McCarthy *et al*., 1986). Second, it may, however, be the case that the presence of indurated silcretes only within Delta outflow channels is also a function of channel architecture. Channel systems provide a location where relatively deep groundwater movement can occur within a confined setting. This, when allied with the potential for large seasonal shifts in the boundary between the vadose and phreatic zones, may explain why massive silcretes occur in channel settings but are not found in the unconfined Delta where the annual lateral spread of floodwater is relatively limited in depth.

Despite the fact that both surface and sub-surface silcretes at Samedupe and Boro Junction occur in a fluvial setting, there is no case for terming these silcretes strictly ‘fluvial’ other than in terms of their location. This study agrees with Summerfield’s (1982, 1983a,b) observation that the Boteti surface silcretes have formed as a result of evaporative concentration in pools, and are thus essentially of pan or lacustrine origin. Likewise, silcrete formation in association with a fluctuating groundwater level is a process which will also occur in pan environments, and cannot therefore be considered exclusive to the fluvial domain. Thus, even though a silcrete occurs in a fluvial setting, it does not necessarily indicate that the duricrust formed in a way that is unique to this type of setting. In conclusion it would seem more appropriate to assume that geomorphological depressions of many origins will be suitable sites for duricrust formation, and that the mechanisms of duricrust emplacement, particularly the controls upon silica precipitation, are of more consequence.

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REFERENCES

Ambrose, G. J. and Flint, R. B. 1981. 'A regressive Miocene lake system and silicified strandlines in northern South Australia; implications for regional stratigraphy and silcrete genesis', *Journal of the Geological Society of Australia*, **28**, 81–94.
Arakel, A. V. 1986. 'Evolution of calcrete in palaeo-drainages of the Lake Napperby area, Central Australia', *Palaeogeography, Palaeoclimatology, Palaeoecology*, **54**, 283–303.
Auzel, M. and Cailleux, A. 1949. 'Silicifications nord-sahariennes', *Bulletin de la Société Géologique de France*, Series 5, **19**, 553–559.
Brückner, W. D. 1966. 'Origins of silcretes in central Australia', *Nature*, **209**, 496–97.
Cooke, C. K. 1979. 'The Stone Age in Botswana: a preliminary survey', *Arnoldia Rhodesia*, **8**, 1–10.
Dincer, T., Hutton, L. and Khupe, B. 1978. 'Study, using stable isotopes, of flow distribution, surface-groundwater relations and evapotranspiration in the Okavango Swamp, Botswana', in *Isotope Hydrology 1978*, International Atomic Energy Authority, Vienna.
Goudie, A. S. 1973. *Duricrusts in Tropical and Subtropical Landscapes*, Clarendon Press, Oxford.
Goudie, A. S. 1983. 'Calcrete', in Goudie, A. S. and Pye, K. (Eds), *Chemical Sediments and Geomorphology*, Academic Press, London, 93–131.
Hutton, J. T., Twidale, C. R. and Milnes, A. R. 1978. 'Characteristics and origin of some Australian silcretes', in Langford-Smith, T. (Ed.), *Silcrete in Australia*, Department of Geography, University of New England, Armidale, New South Wales, 19–39.
Hutton, L. and Dincer, T. 1976. 'Chemistry and stable isotope composition of Okavango Delta waters', in *Investigation of the Okavango Delta as a Primary Water Resource for Botswana*, UNDP/FAO AG:DP/BOT/71/506, Technical Note 23.
Lindqvist, J. K. 1990. 'Deposition and diagenesis of Landslip Hill silcrete, Gore Lignite measures (Miocene), New Zealand', *New Zealand Journal of Geology and Geophysics*, **33**, 137–150.
Livingstone, D. 1858. *Missionary Travels and Researches in South Africa*, Harper Brothers, New York.
McCarthy, T. S. and Ellery, W. N. 1995. 'Sedimentation on the distal reaches of the Okavango Fan, Botswana, and its bearing on calcrete and silcrete (ganister) formation', *Journal of Sedimentary Research*, **A65**, 77–90.
McCarthy, T. S. and Metcalfe, J. 1990. 'Chemical sedimentation in the semi-arid environment of the Okavango Delta, Botswana', *Chemical Geology*, **89**, 157–178.
McCarthy, T. S., McIver, J. R. and Cairncross, B. 1986. 'Carbonate accumulation on islands in the Okavango Delta, Botswana', *South African Journal of Science*, **82**, 588–591.
McCarthy, T. S., McIver, J. R. and Verhagen, B. Th. 1991. 'Groundwater evolution, chemical sedimentation and carbonate brine formation on an island in the Okavango Delta swamp, Botswana', *Applied Geochemistry*, **6**, 577–595.
McDonnell, K. L. 1974. 'Depositional environments of the Triassic Gosford Formation, Sydney Basin', *Journal of the Geological Society of Australia*, **21**, 107–132.
MacGregor, A. M. 1932. 'Geological notes on a circuit of the great Makarikari Salt Pan, Bechuanaland Protectorate', *Transactions of the Geological Society of South Africa*, **33**, 89–102.
Mann, A. W. and Horwitz, R. C. 1979. 'Groundwater calcrete deposits in Australia: some observations from Western Australia', *Journal of the Geological Society of Australia*, **26**, 293–303.
Milnes, A. R. and Thiry, M. 1992. 'Silcretes', in Martini, I. P. and Chesworth, W. (Eds), *Weathering, Soils and Paleosols*, Developments in Earth Surface Processes 2, Elsevier, Amsterdam, 349–377.
Nash, D. J. 1997. 'Groundwater as a geomorphological agent in drylands', in Thomas, D. S. G. (Ed.), *Arid Zone Geomorphology: Process, Form and Change in Drylands*, John Wiley, Chichester, 319–348.
Nash, D. J., Shaw, P. A. and Thomas, D. S. G. 1994a. 'Duricrust development and valley evolution – process–landform links in the Kalahari', *Earth Surface Processes and Landforms*, **19**, 299–317.
Nash, D. J., Thomas, D. S. G. and Shaw, P. A. 1994b. 'Siliceous duricrusts as palaeoclimatic indicators: evidence from the Kalahari Desert of Botswana', *Palaeogeography, Palaeoclimatology, Palaeoecology*, **112**, 279–295.
Ollier, C. D. 1991. 'Aspects of silcrete formation in Australia', *Zeitschrift für Geomorphologie*, **35**, 151–163.
Renaut, R. W., Tiercelin, J. J. and Owen, R. B. 1986. 'Mineral precipitation and diagenesis in the sediments of the Lake Bogoria basin, Kenya Rift Valley', in Frostick, L. E., Renaut, R. W., Reid, I. and Tiercelin, J. J. (Eds), *Sedimentation in the African Rifts*, Blackwell Scientific, Oxford, 159–175.
Sawula, G. and Martins, E. 1991. 'Major ion chemistry of the lower Boro River, Okavango Delta, Botswana', *Freshwater Biology*, **26**, 481–493.
Senior, B. R. 1978. 'Silcrete and chemically weathered sediments in southwest Queensland', in Langford-Smith, T. (Ed.), *Silcrete in Australia*, Department of Geography, University of New England, Armidale, New South Wales, 41–50.
Shaw, P. A. 1984. 'A historical note on the outflows of the Okavango Delta system', *Botswana Notes and Records*, **16**, 127–139.
Shaw, P. A. 1988. 'After the flood: the fluviolacustrine landforms of northern Botswana', *Earth-Science Reviews*, **25**, 449–456.
Shaw, P. A. and Thomas, D. S. G. 1993. 'Geomorphology, sedimentation and tectonics in the Kalahari Rift', *Israel Journal of Earth Sciences*, **41**, 87–94.
Shaw, P. A., Cooke, H. J. and Thomas, D. S. G. 1988. 'Recent advances in the study of Quaternary landforms in Botswana', *Palaeoecology of Africa*, **19**, 15–26.

Shaw, P. A., Cooke, H. J. and Perry, C. C. 1991. 'Microbialitic silcretes in highly alkaline environments: some observations from Sua Pan, Botswana', *South African Journal of Geology*, **93**, 803–808.

Smale, D. 1973. 'Silcretes and associated silica diagenesis in southern Africa and Australia', *Journal of Sedimentary Petrology*, **43**, 1077–1089.

Snowy Mountains Engineering Corporation (SMEC) 1987. *Southern Okavango Integrated Water Development Phase 1, Technical Study Final Report, Volume 1*, Department of Water Affairs, Gaborone, Botswana.

Snowy Mountains Engineering Corporation (SMEC) 1989. *Ecological Zoning – Okavango Delta, 2 Volumes*, Kalahari Conservation Society/Ministry of Local Government and Lands, Gaborone, Botswana.

Stephens, C. G. 1964. 'Silcretes of cental Australia', *Nature*, **203**, 1407.

Stephens, C. G. 1971. 'Laterite and silcrete in Australia: a study of the genetic relationships of laterite and silcrete and their companion materials, and their collective significance in the formation of the weathered mantle, soils, relief and drainage of the Australian continent', *Geoderma*, **5**, 5–52.

Summerfield, M. A. 1982. 'Distribution, nature and genesis of silcrete in arid and semi-arid southern Africa', in Yaalon, D. H. (Ed.), *Aridic Soils and Geomorphic Processes, Catena Supplement*, **1**, 37–65.

Summerfield, M. A. 1983a. 'Silcrete as a palaeoclimatic indicator: evidence from southern Africa', *Palaeogeography, Palaeoclimatology, Palaeoecology*, **41**, 65–79.

Summerfield, M. A. 1983b. 'Silcrete', in Goudie, A. S. and Pye, K. (Eds), *Chemical Sediments and Geomorphology*, Academic Press, London, 59–91.

Thiry, M. and Milnes, A. R. 1991. 'Pedogenic and groundwater silcretes at Stuart Creek opal field, South Australia', *Journal of Sedimentary Petrology*, **61**, 111–127.

Thiry, M., Ayrault, M. B. and Grisoni, J. 1988. 'Ground-water silicification and leaching in sands: example of the Fontainebleau Sand (Oligocene) in the Paris Basin', *Bulletin of the Geological Society of America*, **100**, 1283–1290.

Thomas, D. S. G. and Shaw, P. A. 1991. *The Kalahari Environment*, Cambridge University Press.

Watson, A. and Nash, D. J. 1997. 'Desert crusts and rock varnish', in Thomas, D. S. G. (Ed.), *Arid Zone Geomorphology: Process, Form and Change in Drylands*, John Wiley, Chichester, 69–107.

Wayland, E. J. 1950. 'From an archaeological notebook', *South African Archaeological Bulletin*, **5**, 4–14.

Williams, L. A. and Crerar, D. A. 1985. 'Silica diagenesis, II. General mechanisms', *Journal of Sedimentary Petrology*, **55**, 312–321.

Williams, L. A., Parks, G. A. and Crerar, D. A. 1985. 'Silica diagenesis, I. Solubility controls', *Journal of Sedimentary Petrology*, **55**, 301–311.

Wilson, B. H. and Dincer, T. 1977. 'An introduction to the hydrology and hydrography of the Okavango Delta', in *Symposium on the Okavango Delta*, Botswana Society, Gaborone, Botswana, 33–46.

Wopfner, H. 1978. 'Silcretes of northern South Australia and adjacent regions', in Langford-Smith, T. (Ed.), *Silcrete in Australia*, Department of Geography, University of New England, Armidale, New South Wales, 93–141.

